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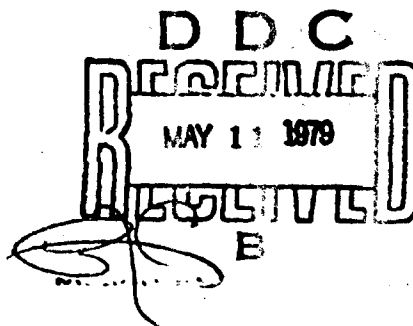
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INFRARED ATTENUATION BY AEROSOLS
IN LIMITED ATMOSPHERIC VISIBILITY:
RELATIONSHIP TO LIQUID WATER CONTENT

Robert E. Roberts
Lynne N. Seekamp

March 1979

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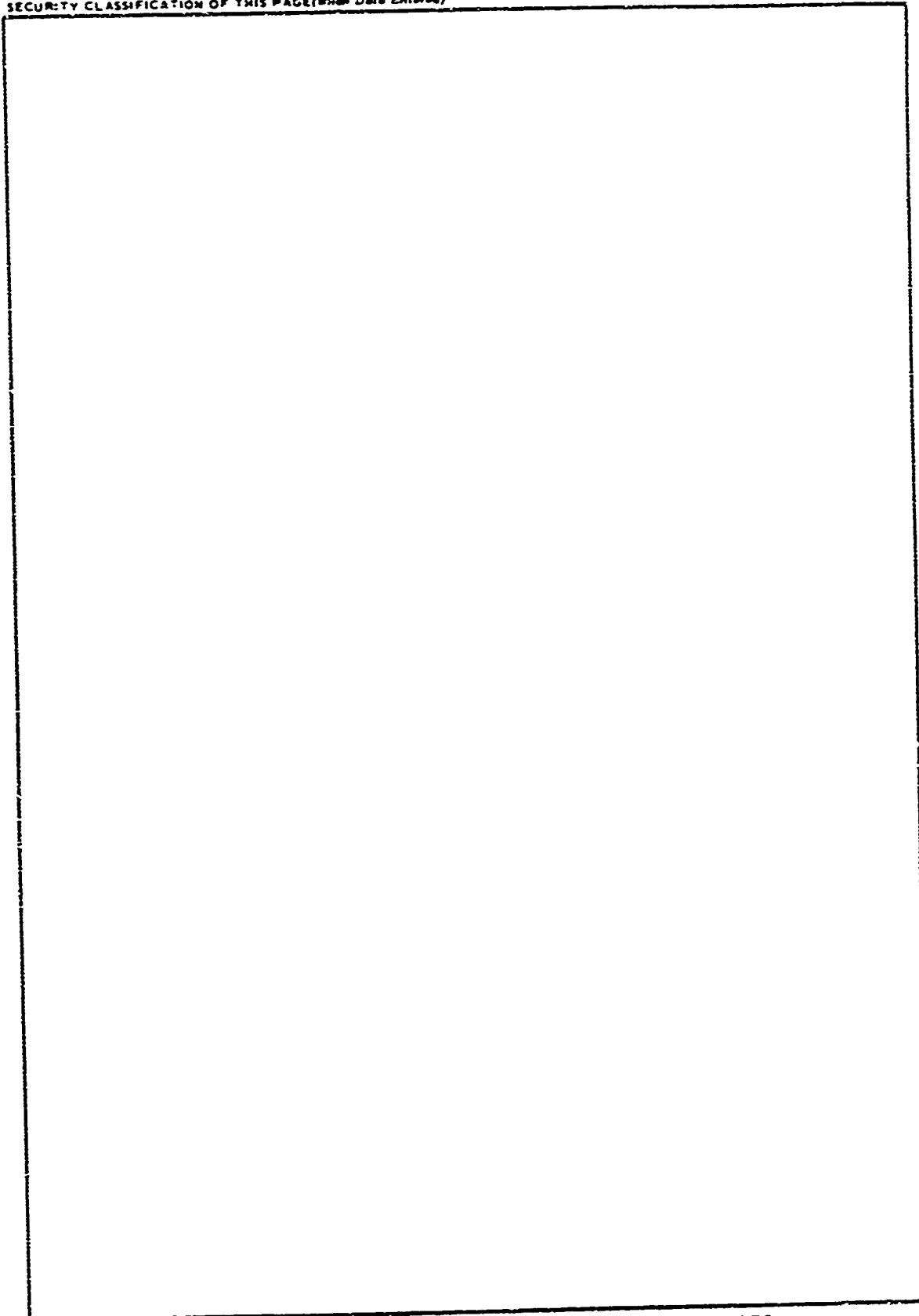
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ABSTRACT

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I. INTRODUCTION

The prediction of multispectral aerosol attenuation in limited atmospheric visibility as typified by water hazes, fogs, and clouds remains an outstanding problem. In principle it is possible, under well-controlled circumstances, to measure the optical composition and size distribution of atmospheric particulates and then to use this information in a Mie calculation to predict the multispectral transmission characteristics. In practice, however, such a particle size distribution measurement is far from routine and proves to be both difficult and inadequate in application due to the spatial and temporal fluctuations associated with the real atmosphere. It would therefore appear to be more practical, if not necessary, to adopt a more phenomenological, albeit approximate, approach to aerosol modeling that does not depend upon direct measurement or detailed description of any particular distribution.

Most current aerosol models erroneously rely upon a single representative particle size distribution. The current LOWTRAN aerosol model (Ref. 1), for example, uses measured optical properties (representative of average continental, rural, urban, or maritime conditions) with a prototypical distribution to construct by means of a Mie computation a scaling model for extrapolation of transmission in the visible wavelength range to transmission in the infrared. The underlying assumption is that for a particular atmospheric condition, such as a continental water haze, the shape or functional form is a fixed and well-known distribution. In many, if not most, cases this is not a valid representation. Unfortunately, the shape or functional

form of the distribution varies over such a wide range that a prototypical distribution, such as a continental haze, is not very representative of aerosol conditions at any particular time or place. For example, in an evolving fog formation the water droplet distribution tends to grow in the sense that there are relatively more large particles as the visibility becomes lower. This is illustrated dramatically in Fig. 1, where we have plotted some representative measurements made in Grafenwöhr, Federal Republic of Germany, over a 12-hour period on 30-31 December 1975 (Ref. 2). Figure 2 shows the same principle for particle size distributions for hazes and radiation fogs from the recent review of Tomasi and Tampieri (Ref. 3). Each of these distributions leads to a different spectral dependence for the aerosol extinction coefficient, as shown explicitly in Fig. 1.

In this paper we propose a simple but general scaling model that takes into account such changes for 8-12 μm infrared extinction but does not depend explicitly upon the selection of any single measured or assumed size distribution. Although the application in this paper will be primarily to water droplet or fog/cloud optical properties, the arguments used to postulate the scaling model are generally valid also for other particulates.

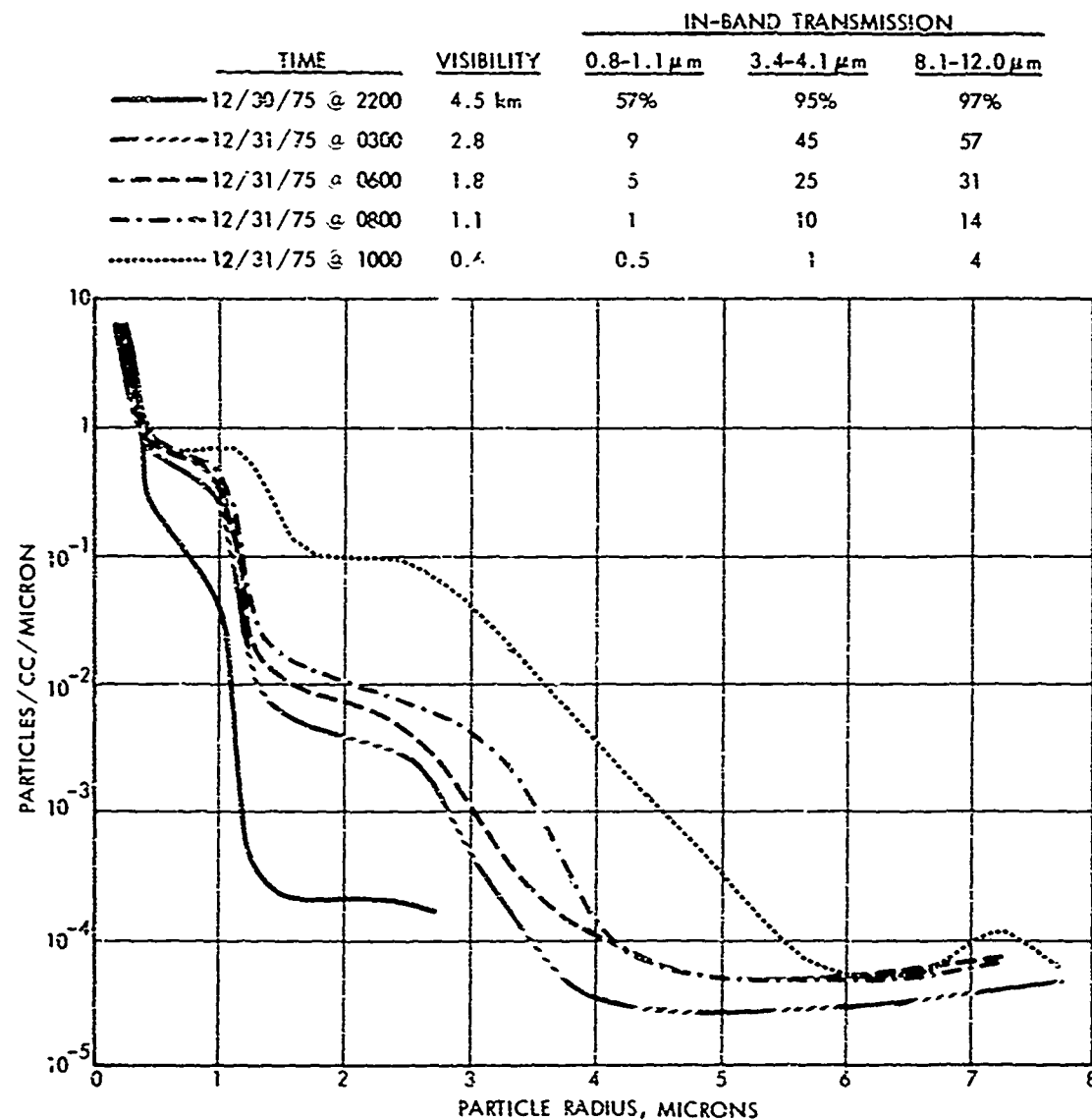
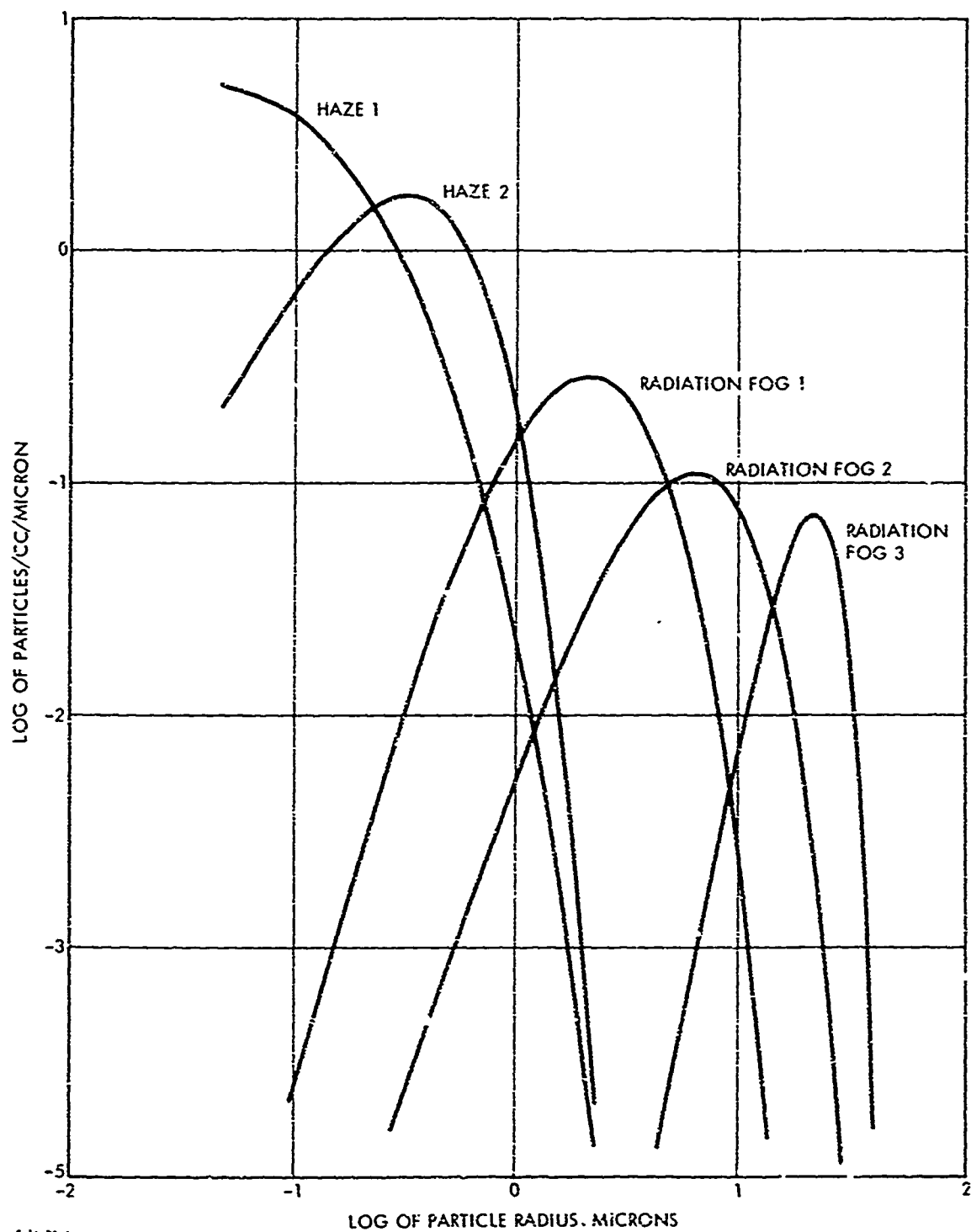


FIGURE 1. Growth of aerosol droplets as fog builds over time, Grafenwöhr, FRG, 30-31 December 1975. The corresponding change in measured transmission is noted accordingly. The visibility as well as the scaling between different spectral bands changes dramatically as the particle size distribution evolves, with a corresponding increase in larger particles. Since the actual particle distribution measurements sample $n(r)$ rather than $r^3n(r)$ in Figs. 1 and 2. A similar plot of $r^3n(r)$ would show maxima towards larger particles than $n(r)$. For example, the case at 10:00 hours (.....) would show a maximum at about 4 μm .



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FIGURE 2. Particle size distributions representative of hazes and radiation fogs (Ref. 3).

II. DISCUSSION

To develop a more flexible model we will recast the aerosol extinction theory in terms of a moment analysis. If one can measure or predict both the entire particle size distribution $n(r)$, where r is the particle radius, and the optical properties of the particulates as characterized by the complex index of refraction, then ideally the problem of predicting the multispectral aerosol extinction coefficients is solved by an application of Mie theory. Alternatively, one can describe the entire distribution by an equivalent knowledge of the complete set of moments $I_k = \int r^k n(r) dr$ for $k = 0, 1, 2, \dots$. One can thus recast the problem by stating that if the set of moments for the distribution as well as optical properties are given, the extinction coefficients can also be obtained. For this equivalence to have any practical significance we must show that the set of moments, or preferably a limited selection of moments, plus optical properties can provide useful information concerning the aerosol extinction coefficient β_{aer} . We would like to show in particular that one specified moment, namely the third moment I_3 or the liquid water content or volume density v , is especially useful for characterizing infrared propagation.

For a specified wavelength λ that is large compared to the typical particle radius r , the Mie extinction cross section is proportional to r^3 ($\sigma_{ext} \sim r^3$) in an absorptive medium (Ref. 4). The total aerosol extinction coefficient β_{aer} is given by the average of the cross section over the particle size distribution $n(r)$. Hence, for λ large compared to r , which should

be appropriate for far IR radiation and small-particle fogs or hazes, the aerosol attenuation at a given wavelength depends primarily upon the third moment I_3 of the distribution, or specifically the total volume or liquid content v of particulates, in a straightforward linear fashion: $\beta_{\text{aer}} \sim I_3 \sim v$. The constant of proportionality is dependent upon the explicit wavelength due to its functional relationship to the complex index of refraction. If we next examine the other extreme, sometimes referred to as the geometric limit, where the particles are typically large compared to the wavelength of the radiation, then large-particle scattering dominates* (Ref. 4), and we have $\sigma_{\text{ext}} = 2\pi r^2$. Once again, a size averaging yields the desired result, related now to the effective area A or second moment I_2 for the given distribution: $\beta_{\text{aer}} \sim I_2 \sim A$.

Since there is such a small change (from I_3 to I_2) in the functional dependence of β_{aer} upon $n(r)$ for the two extreme limits, it is probably not presumptuous to assume that for a particular type of aerosol and spectral region the attenuation or extinction is most critically dependent upon the volume of particulate in the atmospheric path and not so much upon the detailed description of the distribution function. For limited-visibility atmospheric conditions we have generally found a weaker linear correlation between extinction at or near photopic wavelengths and the liquid content. As expected, there is a stronger correlation with the effective area density, $v^{2/3}$. For example, Mie calculations for a set of measured particle distributions such as those illustrated in Fig. 1 yield a best-fit relationship $\beta_{\text{aer}} \sim v^{0.72}$ for $\lambda = 0.55 \mu\text{m}$.

In principle and perhaps in practice, selection of a single moment does not provide a real restriction to the modeling of

*The r^3 dependence can be justified on purely physical grounds by noting that the absorption of light is proportional to the cross section (area) intercepted times the path length traversed through the absorbing medium.

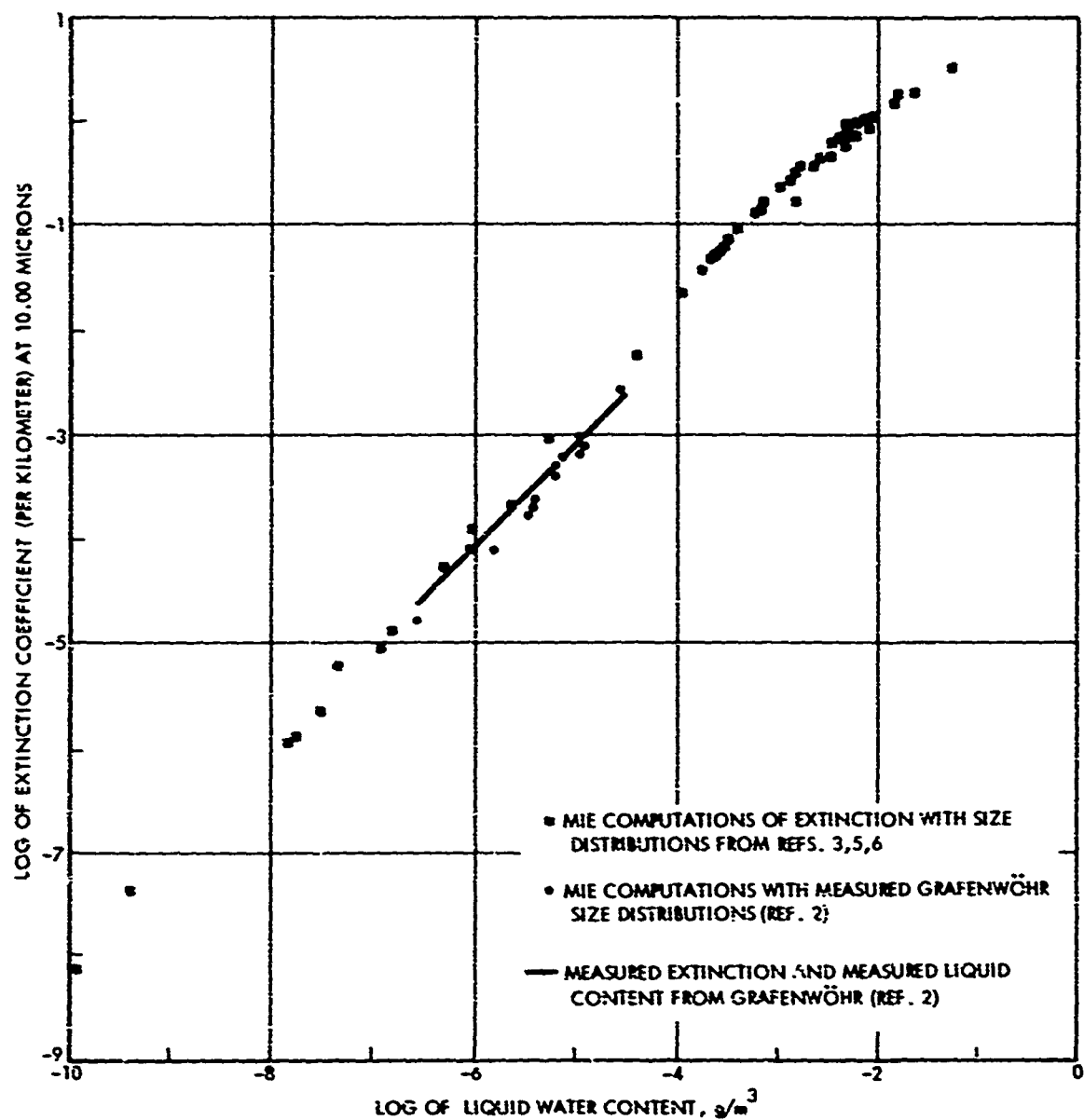
infrared propagation in aerosols. For example, if selection of a single moment such as liquid water content does not provide an adequate accounting of propagation characteristics, it is possible to carry out an analysis based upon two or more moments. One could possibly measure or monitor the moments by using a multiple-frequency light detection and ranging (LIDAR) system.

Using Mie calculations for 58 different particle size distributions representative of hazes, fogs, and clouds (Refs. 3, 5, 6), as well as independent field measurements of particle sizes made in Grafenwöhr, FRG, during a 12-hour period (Ref. 2), we have established that a strong relationship does exist between the total volume content of the particulate along the transmission path and the aerosol extinction coefficient. Figure 3 illustrates the correlation between β_{aer} at 10 μm and liquid content and the subsequent independence of the specifics of $n(r)$. The size distributions are characterized by mode radii ranging over approximately four orders of magnitude up to 20 μm . The Grafenwöhr field measurements (●) are in excellent agreement with the theoretical distributions of Refs. 3, 5 and 6 (■).

At Grafenwöhr on 30-31 December 1975, when the particle distributions shown in Fig. 1 were measured, a simultaneous set of 8-12 μm extinction measurements was carried out over an 1140-m transmission path (Ref. 2). The straight line in Fig. 3 is the regression ($\rho = 0.88$ for 12 data points) based upon the Grafenwöhr measured size distributions (to yield the measured liquid content) and measured extinction. The relationship is the following:

$$\epsilon_{8-12 \mu\text{m}} = 139 v^{1.03},$$

where v is in grams per cubic meter. This is in very good agreement with the scaling law based upon Mie calculations with measured or assumed distributions. Since our initial investigations (Ref. 2) suggesting the critical role of



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FIGURE 3. Log of β_{aer} at 10 μm versus log of liquid water content. The distributions have been normalized to a total number density of one particle per cubic centimeter.

atmospheric liquid water content in IR propagation, other workers have demonstrated a similar strong correlation between aerosol extinction and liquid water content for maritime environments as well (Ref. 7).

III. CONCLUSIONS

We have provided a variety of experimental and theoretical data to demonstrate that to a good approximation knowledge of the atmospheric liquid water content is in fact sufficient to determine aerosol extinction of the far infrared when visibility is limited by water hazes, fogs, and clouds. Detailed knowledge of the particle size distribution is unnecessary. Thus, the linear dependence of β_{aer} upon liquid water content suggests that a simple measurement of a quantity related to the volume of particulate along the transmission path (i.e., grams per cubic meter) could provide a direct measure of the IR transmission characteristics.

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